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A THEORETICAL MODEL FOR THE MAGNETIC DECLINATION EFFECT IN THE IONOSPHERIC F REGION

BY

RICHARD A. GOLDBERG

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Richard A. Goldberg
Laboratory for Space Sciences
NASA-Goddard Space Flight Center
Greenbelt, Maryland

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ABSTRACT

It is well known that the equatorial F region of the ionosphere exhibits geomagnetic control when studied using magnetic inclination or dip. This phenomenon, often referred to as the geomagnetic anomaly, exhibits itself more strongly in the topside region due to the reduced effect of collisions. Studies of foF2 have also indicated that magnetic declination influences the behavior of the F region ionosphere, and furthermore that this effect is not limited to low latitudes.

We have previously demonstrated that the geomagnetic anomaly distribution can be described in terms of a non-accelerating electron density distribution under the influence of electric, magnetic and gravitational forces and the effects of production and loss. In this work, we now suggest that these individual magnetically aligned planes of ionization can be correlated by a longitudinal density distribution as a boundary condition, this distribution being geographically oriented because its variations are primarily under solar control. This concept is introduced into the equations by means of a current system, necessary to create a balance of forces under equilibrium conditions. The intermixing of a geographically controlled longitudinal distribution with a geomagnetically controlled latitudinal distribution is then found to provide a consistent picture of the declination effects previously reported in the literature. Furthermore, it enables shapes and behavior of the distribution, heretofore unstudied, to be predicted.

Author

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INTRODUCTION

Eyfrig (1963b) has briefly reviewed the historical sequence in the discovery of geomagnetic control as a force in establishing the distributions and behavior of electron density seen in the F2 region. He reports that this control was first noted by I. Ranzi (1939) and O. Burkard (1941). Furthermore, this was independently observed by K. Maeda, H. Uyeda, and H. Sinkawa as early as 1942. These early studies were concerned mainly with longitudinal differences in magnetic field and did not actually establish the equatorial density distribution with dip (geomagnetic anomaly) as we know it today. Appleton (1946) was the first to recognize the convenience of using magnetic dip instead of geographic latitude as a more suitable parameter to study latitudinal variations in foF2 and thereby discovered the "anomaly."

There is now no question that magnetic dip is the most suitable simple parameter with which to study the F2 equatorial ionosphere and numerous papers have been published providing evidence for this. With the advent of the Alouette I topside sounder, it has become clear that this geomagnetic control is even more dominant in the topside than in the bottomside of the F2 region. This is seen by studying constant height profiles of density with dip where we find (as first reported by King, et al 1963) that the latitudinal crests of the anomaly actually align along a field line.

Unfortunately, although we observe very well defined properties of the anomaly with magnetic dip, we also find many F2 properties which dip dependence alone is incapable of organizing. For example, we would expect that during dip equinox, the anomaly would be symmetric with respect to the dip equator, yet Lyon and Thomas (1963) have shown that this symmetry can be less evident during dip equinox than geographic equinox, at least for high sunsport number on the 75th meridian west. Furthermore, it is well known that the times of occurrence and disappearance of the anomaly vary significantly in different sectors of the world, the duration of its presence being two or three hours longer in the Africian and Asian zones than in the American zone (Lyon and Thomas, 1963, Rao and Malthotra, 1964). Comparison of the results of King et al (1963) with those of Lockwood and Nelms (1964), using Alouette I topside sounder data, shows that similar results also apply to constant height latitudinal profiles in the topside. In addition, Rastogi and Sanatani (1963) have studied the diurnal behavior of foF2 for various world wide stations possessing identical dip and

found strong differences depending on longitude. If we are to assume that solar influence through production, heating, ion composition and temperature are all approximately equal in the three zones at corresponding altitudes and geographic latitudes, we are forced to conclude that magnetic control, through variations in declination, must have a share of the responsibility in causing such longitudinal differences.

Eyfrig (1963a,b) has indeed demonstrated that the behavior of foF2 significantly varies as a function of magnetic declination. In these excellent morphological studies, he has shown how diurnal variations in the values of foF2 are consistently much less for a west declination station than for an east declination station in the northern hemisphere, provided both stations are located at identical values of dip and geographic latitude. Furthermore, he notes that the declination effect inverts itself between northern and southern hemispheres, i.e., west declination stations in the northern hemisphere show results similar to east declination stations in the southern hemisphere during equinoctial months. Also, conjugate stations in dip exhibit quite different behavior of foF2 in general, since they are not conjugate in declination. Finally, we note that Eyfrig's results show stronger declination influence at mid-latitudes than in equatorial regions.

In several recent papers (Goldberg, Kendall, and Schmerling, 1964, Chandra and Goldberg, 1964, Goldberg, 1965a and 1965b), we have demonstrated how the topside portion of the geomagnetic anomaly can be described as the steady state density distribution for a plasma under the influence of gravitational, electric, and magnetic fields and production and loss, when collisions of the plasma with the neutral medium are considered negligible. In the most recent paper of this series, Goldberg (1965b), we have also derived the expressions necessary to describe the longitudinal current system which must exist to support the steady state distribution in the configuration of the geomagnetic anomaly. The purpose of this paper is to extend this work including the effects of latitudinal and vertical current components, and show how a consistent model for the F region current system in conjunction with magnetic field declination can account for the unusual declination effects listed above. This will lead to an explanation for the declination effect based on a combination of magnetic and solar effects. In the process of studying these equations, we will also attempt to predict the observed differences we should expect to find at different declinations for vertical and latitudinal slopes leading to description of other F2 region properties heretofore unnoticed.

FUNDAMENTAL CONCEPTS

We consider those equations which describe the momentum transfer of a minor constituent electron-ion plasma flowing in a neutral medium under steady

state conditions (by steady state, we imply complete neglect of accelerations but still allow the possibility of slow time varying changes in density, temperatures and composition). The major forces assumed to be governing the plasma flow are electric, gravitational and magnetic. Production and/or loss can also be incorporated into (although not described by) the equations by means of empirical or assumed boundary conditions. We neglect collisions of charged particles with the neutral medium but do not disallow collisions between electrons and ions. Furthermore, we treat the collisions as elastic and two-body. Finally, we treat pressure as an isotropic scalar by neglecting off-diagonal viscous terms in the pressure tensor.

The assumptions discussed above have led to equations which appear to describe the topside equatorial F region ionosphere with a high degree of success, both qualitatively and quantitatively. This work will not be reviewed here but instead, the reader is referred to Goldberg (1965b), for a general discussion of the previous work plus a detailed review of the derivation from which the equations we will employ in this work arise. Hence, from Goldberg (1965b) we can write

$$-\frac{\nabla N}{N} - \frac{\nabla \tau}{\tau} + \frac{\vec{j} \times \vec{B}}{2k\tau} - \frac{\vec{i}_r}{2H_\tau} = 0 \tag{1}$$

where N is either electron or ion density, τ is the average temperature of electrons and ions, $\tau = (T_e + T_i)/2$, $\vec{B}$ is the earth's magnetic field, k is Boltzmann's constant, and $\vec{i}_r$ is a unit vector in the radial direction from the center of the earth. Furthermore, $\vec{j}$ is defined by

$$\vec{j} = e\,(\vec{v}_i - \vec{v}_e) \tag{2}$$

where e is the magnitude of the electron charge and $\vec{v}_i$ and $\vec{v}_e$ are ion and electron velocities respectively. In the work which follows, $\vec{j}$ and its components will often be referred to as current although it actually is current per unit density. However, this distinction will not affect the conclusions. Finally, H_τ is a scale height given by

$$H_\tau = k\tau/m_i g \tag{3}$$

where m_i is the mean molecular mass of the ionizable constituents and g is the gravitational acceleration.

Equation (1) can be resolved into three orthogonal spherical polar components. As previously demonstrated in Goldberg (1965b), we can select the simple centered dipole model for the earth's magnetic field giving the field a northward sense and aligning our coordinate system with $-\vec{B}$ (the magnetic north pole actually lies in the geographic southern hemisphere). Then $\vec{B}$ can be written as

$$\vec{B} = \left(-\frac{\mu_0}{2\pi}\frac{M_p}{r^3}\cos\theta,\ -\frac{\mu_0}{4\pi}\frac{M_p}{r^3}\sin\theta,\ 0\right) \tag{4}$$

where M_p and μ_0 are magnetic constants. Equation (1) now becomes, in component form,

$$\frac{1}{N}\frac{\partial N}{\partial r} + \frac{1}{\tau}\frac{\partial \tau}{\partial r} + \frac{1}{2H_\tau} - \frac{\mu_0 M_p}{8\pi k\tau}\frac{\sin\theta}{r^3}\, j_\phi = 0 \tag{5}$$

$$\frac{1}{N}\frac{\partial N}{\partial \theta} + \frac{1}{\tau}\frac{\partial \tau}{\partial \theta} + \frac{\mu_0 M_p}{4\pi k\tau}\frac{\cos\theta}{r^2}\, j_\phi = 0 \tag{6}$$

$$\frac{1}{N}\frac{\partial N}{\partial \phi} + \frac{1}{\tau}\frac{\partial \tau}{\partial \phi} + \frac{\mu_0 M_p}{4\pi k\tau}\left(\frac{\sin^2\theta}{2r^2}\, j_r - \frac{\cos\theta\sin\theta}{r^2}\, j_\theta\right) = 0 \tag{7}$$

The above equations have been discussed in detail in Goldberg (1965b) with regard to the j_ϕ component of current which must exist to support the geomagnetic anomaly as a steady state density distribution. It has been shown that j_ϕ must be positive (eastward) within the crests and negative (westward) outside of the crests of the anomaly to satisfy the physical assumptions leading to (6). We also note here that j_r, j_θ, and j_ϕ represent the three components of a current perpendicular to $\vec{B}$ since no information concerning parallel components of $\vec{j}$ (if they exist) are obtainable from (1) nor do they affect conclusions arrived from (1) directly. In the next sections, we will extend the concept of a current system even further and demonstrate how solar control of the distribution (and hence of the current system) in early morning and late evening can provide a consistent model for describing the observations of foF2 by Eyfrig as well as predicting other properties of the anomaly at dip equinox.

THEORETICAL ASSUMPTIONS AND CONSIDERATIONS

Equations (5), (6), and (7) represent the steady state properties of the F region density and temperature distributions in a magnetically aligned coordinate system. The advantage of such a coordinate system is apparent; we observe that the steady state equilibrium distribution in a particular magnetic meridional (r, θ) plane is independent of the behavior of such a distribution in any other (r, θ) plane. This result remains valid as long as we are able to neglect the nonlinear and time dependent terms in the original momentum transfer equation. Furthermore, if we assume that each (r, θ) plane distribution is slowly varying with time, then at any instant of the day we can take a "snapshot" of the distribution and find it close to an equilibrium state. (Such an assumption should hold true at all times of the day except perhaps during sunrise). The above considerations allow us to think of the distribution around the earth as being fixed in space, so that each (r, θ) plane rotates with the earth, passing on its present distribution to the plane just behind it and picking up the distribution of the plane just ahead of it. In such a case, we can relate time to longitude interchangeably to a first approximation, and the distribution seen in any plane mapped out as a function of local time is equivalent to the distribution with longitude at any instant of time, provided we correct for the skewness or relative declination between the geographic and geomagnetic longitude.

We select that system which describes one plane as a function of time because there is an advantage to be gained over studying the fixed system in space. In the selected system, we can study the magnetic (r, θ) planes most closely related to magnetic or dip equinox and hence, remove any latitudinal asymmetry effects introduced by solar control. Furthermore, in this system, we can observe the skewness between geographic and magnetic coordinates as a fixed property rather than a variable behavior.

Since every (r, θ) plane in the magnetic system contains a quasi-steady state distribution independent of that in any other (r, θ) plane, the correlation of the distribution between planes must be applied as a boundary condition in the longitudinal direction. Furthermore, the major control of the distribution in this direction seems solar (or geographic) rather than magnetic so that we must relate properties of the distribution aligned magnetically with those aligned geographically. As we shall see, it is this skewness between the two preferred coordinate systems that is responsible for the properties we wish to explain.

At this point it is desirable to compare the equations governing the density and temperature distributions in the geomagnetic coordinate system with those governing the same distributions in some other coordinate system obtained by a simple Eulerian rotational transformation, e.g., the geographic coordinate system. First let us rewrite (5), (6), and (7) as

$$K_r = -m_i g - j_\phi B_\theta \tag{8}$$

$$K_\theta = j_\phi B_r \tag{9}$$

$$K_\phi = j_r B_\theta - j_\theta B_r \tag{10}$$

where we have incorporated (4) and defined K_r, K_θ, and K_ϕ as logarithmic pressure slopes, i.e.

$$K_r \equiv 2k\tau\, \partial(\ln N\tau)/\partial r \tag{11}$$

$$K_\theta \equiv 2k\tau\, \partial(\ln N\tau)/r\partial\theta \tag{12}$$

$$K_\phi \equiv 2k\tau\, \partial(\ln N\tau)/r \sin\theta\, \partial\phi \tag{13}$$

In the work which follows, we will refer to K_r, K_θ, and K_ϕ as pressure gradients and consider the major contribution of each component to be the logarithmic density gradient. This is a reasonable assumption for K_r since τ is known to be nearly isothermal vertically in the topside F region. It also seems reasonable to accept this assumption as a first approximation for K_θ, if we keep in mind the possibility that latitudinal temperature gradients of the same order of magnitude as latitudinal density gradients could alter or enhance the results significantly. Finally, we know that the temperature and density directions are additive in the K_ϕ component, so that longitudinal temperature gradients cannot alter the conclusions of this work.

Equations (8), (9), and (10) represent the logarithmic slopes of density and temperature in the magnetic coordinate system (r, θ, ϕ). By referring to (1) once again, we note that three component equations can also be written in any other spherical polar orthogonal coordinate system, i.e.,

$$K_r = -m_i g + j_{\theta'} B_{\phi'} - j_{\phi'} B_{\theta'} \tag{14}$$

$$K_{\theta'} = j_{\phi'} B_r - j_r B_{\phi'} \tag{15}$$

$$K_{\phi}' = j_r B_{\theta}' - j_{\theta}' B_r \tag{16}$$

where the primes refer to the new coordinate system. We leave r nonprimed because radial behavior is unaltered by a simple rotation in the (θ, ϕ) plane. Hence, (8) and (14) provide expressions for the same quantity, K_r, in two different coordinate systems.

THE CURRENT MODEL

In this section, we introduce and discuss a closed current system capable of describing, in a fully consistent manner, the physical phenomena normally observed with respect to magnetic dip and declination under quasi-steady state conditions. In understanding this current system, we must be aware of its magnitude; the currents to be discussed are extremely small by ionospheric E region standards, capable of producing local fluctuations in the magnetic field of only $\Delta B/B \sim 10^{-12}$. Yet, at the same time, such currents, possessing magnitudes far too small to be detected by direct measurement, are capable of producing $\vec{j} \times \vec{B}$ forces of the same order of magnitude as the other forces listed in (1) and hence, are extremely important by F region standards.

We note from Goldberg (1965b) that the midday current system necessary to support the latitudinal pressure gradients associated with the equinoctial geomagnetic anomaly must include a magnetic eastward component (j_{ϕ}) on the equatorial side of the anomaly crests and a westward component ($-j_{\phi}$) above the latitudes of the crests. This can also be seen readily from (9). Because of current continuity requirements, such a midday current structure is suggestive of current loops which flow counterclockwise in the northern hemisphere and clockwise in the southern hemisphere when viewed from above.

To check the consistency of the above model with the quasi-steady state results given by (8)-(10) or (14)-(16), we must investigate these equations during both morning and evening conditions. We review that the anomaly is seen to form and build up sometime during the morning hours following sunrise from a very nearly horizontally stratified distribution. In the late evening hours, the reverse situation occurs, with the latitudinal pressure gradients rapidly decaying into a horizontally stratified distribution. Simultaneous with the buildup and decay of the latitudinal gradients, it is well known that the longitudinal pressure increases and decreases respectively. This latter effect, of course, is due primarily to differences in pressure between day and night. Since pressure differences between day and night distributions are primarily caused by solar control, we would expect such longitudinal gradients to be aligned in a geographic sense.

ıence, our primary component of longitudinal pressure gradient is $K_{\phi'}$ given by (16), with K_ϕ, given by (10), being a projection of $K_{\phi'}$ depending on magnetic declination.

Let us first consider the equations with the neglect of j_r. Since j_r cannot contribute directly to the vertical slope, as seen in (8) and (14), nor to the magnetic latitudinal slope given by (9), we can neglect it for convenience with no inconsistency nor change in the conclusions which follow. Furthermore, we can argue that $j_{\theta'}$ must exist to create the declination effect, as will be seen in the following sections, and hence it must dominate the sense of the right hand side of (16) in all regions where the declination effect is a strongly observed phenomenon. We should note from (16) that near the equator where $B_r \to 0$, j_r must occur in the morning and late evening periods to balance $K_{\phi'}$. However, this is just the region in which Eyfrig has found the declination effect to be extremely weak.

By neglect of j_r, we see that a positive $K_{\phi'}$ (morning) implies a positive $j_{\theta'}$ in the northern hemisphere and a negative $j_{\theta'}$ in the southern hemisphere, both implying a current flow toward the equator. The reverse situation occurs for $-K_{\phi'}$ in the evening hours. Hence, the longitudinal pressure gradients during morning and evening hours are supported by currents attempting to achieve equilibrium consistent with those currents expected at midday. Furthermore, because the pressure gradient K_θ is of the same order of magnitude as K_ϕ, with differences possibly being attributable to vertical current (j_r) contributions, it appears that this current system might be completely closed in the F region with very little assistance from external forces. Finally, because $K_{\phi'}$ is aligned geographically, the latitudinal current flow will be symmetric about the geographic rather than the geomagnetic equator. This latter point is important, since it is this geographic alignment which is required to interpret the declination effect.

To review, we have suggested an F region current system flowing so as to appear, when viewed from above, counterclockwise in a horizontal (θ, ϕ) plane in the northern hemisphere and clockwise in the southern hemisphere. We have demonstrated how such a current system is fully consistent with the longitudinal pressure gradients observed in the morning and evening hours and the latitudinal pressure gradients observed at midday. Although the midday current flows longitudinally in a magnetic sense because the latitudinal pressure gradients are magnetically aligned, we have argued that the perpendicular latitudinal current components occurring in the morning and evening hours must be geographically aligned, i.e., symmetric about the geographic equator at equinox, since the pressure gradients giving rise to these currents are longitudinal in a geographical sense. In the next section, we will deal primarily with the latitudinal component of current, and demonstrate how its geographical alignment can give rise to the magnetic declination effect.

RESULTS AND DISCUSSION

A. Effects on the Vertical Distribution

In the ideal case, we can think of two stations having the same magnetic dip, geographic latitude, local time, but opposite declination. Two pairs of such stations, one pair in the northern hemisphere and the other in the southern hemisphere, are represented in Figure 1. For simplicity, the southern stations are considered conjugate in latitude (both magnetic and geographic) to the northern ones.

Reference to (1) informs us that the force ($\vec{F}$), represented by $\vec{j} \times \vec{B}$, will oppose gravity when it has a component radially outward (positive) and will add to the effect of gravity when its radial component is inward (negative). We also note that any j_r component present will have no direct effect on $\vec{F}$ and that any j_ϕ component present will have a similar contribution (at least in direction) to $\vec{F}$ at all four stations illustrated. Hence, we have chosen to represent $\vec{j}$ in Figure 1 as purely latitudinal (geographic) with no loss of generality in the results which follow.

We observe from Figure 1 and equation (1) that during the morning hours, an east declination station in the northern hemisphere will possess a vertical topside distribution having a logarithmic slope smaller in absolute magnitude than that of a west declination station in the same hemisphere, all other conditions being equivalent. We also note that the reverse situation occurs simultaneously in the southern hemisphere. Table I summarizes the conclusions arrived at from Figure 1 and also includes the expected evening behavior. In evening, we find the effect in each hemisphere to be reversed from that present in the morning.

The results of Eyfrig (1963a,b) concerning foF2 behavior with regard to declination are summarized in Table II. By comparison of Tables I and II we observe that an enhanced vertical slope always corresponds to a reduced value of foF2 and vice-versa. This inverse correspondence between a theoretical result concerning vertical slope and a measured result concerning foF2 can be resolved as follows:

The bottomside of the F2 ionospheric layer is primarily controlled by the effects of production, loss, and collisions with the neutral medium. It seems reasonable to postulate that below a specific height in this region, the vertical slope of the distribution is so thoroughly dominated by these effects that transport is nondetectable as an influence; hence the layer is nearly horizontally stratified. As we ascend from this horizontally stratified region, we begin to observe an ever increasing influence of transport on the distribution. Since the vertical transport influence is stronger in declination regions where $\vec{j} \times \vec{B}$ and

gravity are additive than in regions where they are subtractive, we would expect the F2 peak to form at a slightly lower height and exhibit a more rapid curvature into the topside configuration in the additive region. Once we rise into the topside where transport is the dominant influence shaping the distribution, we can expect a more rapid decay for the vertical distribution located in the additive region than that located in the subtractive. Examples of this behavior are illustrated in Figure 2, where we find complete consistency with the results of Tables I and II.

As we climb further above F2, the density difference will increase without limit unless we reach a level above which the currents are negligible. This appears to occur at the top of the geomagnetic anomaly, above which the latitudinal distribution is more nearly horizontally stratified. Hence, we would expect the logarithmic vertical density distribution to fall off with parallel slopes at all equivalent declinations once we are above this level; at least until altitudes are reached in which oxygen is no longer a major constituent.

Eyfrig (1963a,b) has also noticed additional properties in the foF2 behavior which can be explained on the basis of the results discussed herein. He first notices that during the afternoon hours there is little difference in foF2 values between stations of east and west declination. This is illustrated in Figure 3 for Boulder and Washington. He also observes that the declination effect is absent for a shorter period in midafternoon at stations of midlatitude than at stations of low latitude, and furthermore, that the overall declination effect is stronger at midlatitudes.

The absence of the declination effect during midafternoon is not surprising since this is the period of the day during which longitudinal pressure gradients, and thus geographically aligned latitudinal currents, should be minimum. Next, since the ionosphere is more sensitive to solar zenith angle variations when the zenith angle is large, and since the zenith angle is small for a shorter period of midday at the higher latitudes, it seems reasonable to expect longitudinal pressure gradients to be absent at higher latitudes for a shorter period during the afternoon. Finally, the stronger declination effect observed at midlatitudes can be explained by referring to (16). Since $B_r \to 0$ in the equatorial regions, strong longitudinal pressure gradients will give rise to weak j_θ components of current. This implies that the major portion of current generated by longitudinal pressure gradients in the equatorial region will be vertical, but as we have already seen, vertical currents cannot alter or contribute to the declination effect.

Table I

Vertical slope changes of the F region density distribution due to declination as function of time and hemisphere. Results given are relative to the zero declination case.

Declination	Time	Hemisphere	Effect on Slope Magnitude
East	Morning	Northern	Reduction
East	Evening	Northern	Increase
West	Morning	Northern	Increase
West	Evening	Northern	Reduction
East	Morning	Southern	Increase
East	Evening	Southern	Reduction
West	Morning	Southern	Reduction
West	Evening	Southern	Increase

Table II

A summary of the results reported by Eyfrig (1963b) for variation of foF2 due to declination as a function of time and hemisphere. Results given are relative to the zero declination case.

Declination	Time	Hemisphere	Effect on foF2
East	Morning	Northern	Increase
East	Evening	Northern	Reduction
West	Morning	Northern	Reduction
West	Evening	Northern	Increase
East	Morning	Southern	Reduction
East	Evening	Southern	Increase
West	Morning	Southern	Increase
West	Evening	Southern	Reduction

B. Effects on the Latitudinal Distribution

Let us view a specific magnetic meridian on a geographic coordinate system at three different times of day; morning, mid-afternoon and late evening. Such a model is represented in Figure 4. We once again employ a current model whose latitudinal component is symmetric about the geographic equator, but whose longitudinal component aligns magnetically. For simplicity we have chosen that magnetic meridian along which the magnetic equator crosses with the geographic equator so that equinox can occur both magnetically and geographically at one time.

To study the properties of the anomaly let us first view the morning buildup during which strong components of j_θ exist. We select an east declination meridian recognizing that all results will reverse for a west declination meridian. In Figure 4 we have marked four points along a geographic meridian and assumed that the declination is nearly the same at all points. Points "a" and "d" mark positions outside of the anomaly crests at identical latitudes in both hemispheres. Points "b" and "c" are two corresponding points lying within the crests of the anomaly. At some instant of morning local time we study the magnetic component j_ϕ at the four points. The vector triangles show clearly that $j_{\phi a} < j_{\phi d}$ and $j_{\phi b} > j_{\phi c}$. Hence, using (9), the logarithmic slope with geomagnetic latitude at "a_1" will be less than the slope at the corresponding southern hemisphere point "d_1." Similarly, the slope at "c_1" will be less than at "b_1."

A study of points "a_3," "b_3," "c_3," and "d_3" (late evening) produces the reverse results, viz. $j_{\phi a} > j_{\phi d}$ and $j_{\phi b} < j_{\phi c}$. Finally, in mid-afternoon, we notice that j_ϕ is perfectly symmetric about the equator. Furthermore, as long as j is parallel at identical latitudes in both hemispheres, this will be true, regardless of whether its direction is more geographically or more magnetically aligned. Table III summarizes the results listed above.

We now assume that the focus of the current system lies at a fixed latitude for a given height at all times of day and furthermore, that the trough of the anomaly must lie on the geomagnetic equator (these assumptions seem reasonable on the basis of foF2 studies). We can then produce a unique representation of the anomaly under the conditions given in Table III. This is illustrated in Figure 5. We note that a higher crest must occur in the northern hemisphere than in the southern hemisphere in morning for an east declination meridian and that this will reverse in the late evening hours. West declination meridians will exhibit similar properties in a reverse sense. In mid-afternoon at dip equinox, we expect a nearly symmetric situation for either declination.

Table III

Ratio of northern to southern hemisphere latitudinal slope magnitudes at corresponding latitudes (both mid and low) under equinox conditions. Refer to Figures 4 and 5 for designation of a, b, c, and d and the origin of the results tabulated here.

Declination	Time	Midlatitude Ratio $K_{\phi a}/K_{\phi d}$	Low Latitude Ratio $K_{\phi b}/K_{\phi c}$
East	Morning	<1 (less than)	>1 (greater than)
East	Afternoon	1	1
East	Evening	>1	<1
West	Morning	>1	<1
West	Afternoon	1	1
West	Evening	<1	>1

Next, if the current component j_θ weakens close to the equator for reasons discussed in a previous section, we would not expect the anomaly to exhibit much asymmetry within the crests, even in regions of high declination. We also note that the curves in Figure 5 need not cross at the equator, but could conceivably be shifted from one another on the ordinate axis.

The effects discussed above should increase for meridians of higher declination and should not occur in regions of low declination where the isoclines of the earth's magnetic field run nearly parallel to the geographic equator. Figure 6 illustrates the isoclines of the earth's magnetic field plotted on geographic coordinates. The angle between isocline normals and geographic meridians can be thought of as declination. We note that both the African and Asian zones exhibit similar properties, having small declination values which exhibit very small changes with longitude. The American zone, on the other hand, shows a wide range of declination values varying very rapidly from east to west as we move eastward. It is well known that the Asian and African zones exhibit very similar properties and behavior of density from studies of the geomagnetic anomaly using foF2. Furthermore, the American zone shows considerably different results. We now suggest that such differences can be attributed to the results outlined above.

As an example, consider the observation that the anomaly appears to form at an earlier hour in the Asian-African zone and then appears to disappear at a later hour than in the American zone. The data taken for such results can only

be obtained using a series of stations which vary widely in geographic longitude. In the Asian-African zone this variation is not serious since declinations are quite small everywhere. Hence, a dip plot made from a group of stations varying widely in longitude should produce the normal behavior of the anomaly, that which we would observe studying it along a single geographic meridian at low declination. The wide variation in longitude of stations used to study the foF2 anomaly in the American zone has far more serious consequences, however. Here, distributions associated with east declination stations are mixed with those of west declination stations, producing a dip distribution which is a random mixing of points using the two asymmetric curves A and C, shown in Figure 5. Hence, it becomes difficult to define the anomaly from this data except at those hours of the day when j_θ is unimportant so that both curves approach B in appearance. We suggest that the anomaly would be observable in the American zone at the same early hours it becomes observable in the Asian and African zones provided we select data points along a path of uniform declination. Furthermore, it would look identical at all points of the earth where declination is the same, having an appearance predicted by Figure 5.

SUMMARY AND CONCLUSIONS

In the magnetic (r, θ) plane, the F region distribution of electrons and ions form a shape known as the geomagnetic anomaly under conditions associated with the quasi-steady state equilibrium of diffusive transport. Furthermore, the world-wide correlation from one plane to another can be applied as a boundary condition using information derived from the component of the transport equation normal to the magnetic field. To determine such a boundary condition, it seems reasonable to suppose that the longitudinal gradients of density and temperature be aligned geographically rather than magnetically, i.e., they should primarily be controlled by the sun. The results herein reflect the effect of mixing a longitudinal geographically controlled distribution with a latitudinal geomagnetically controlled distribution.

We have shown that under the assumptions made, an F region current system is necessary to support the vertical and horizontal density gradients caused by quasi-steady state transport under F region controlling influences. This current system, when projected into the horizontal plane, exhibits a focus near midday at a latitude depending upon the height of the plane of projection. Furthermore, this current flow, when plotted on a longitudinal or diurnal scale, moves eastward at latitudes on the equatorial side of the foci and westward above the foci, closing toward the equator in the morning and away from the equator in the evening. We then observe these closings to be consistent in both direction and magnitude with the pressure gradients known to exist in the F region of the ionosphere.

The assumption of geographically controlled longitudinal pressure gradients in the morning and late evening hours must be introduced in order to obtain non-conjugate behavior with declination and between opposite hemispheres. This asymmetry should then occur even at times of dip or geomagnetic equinox. Specifically, this assumption provides the following results:

1. There is a difference in vertical and latitudinal (magnetic) slope behavior for pressure distributions at stations of opposite declination in the same hemisphere.

2. This behavior is found to reverse between morning and late evening.

3. The behavior of east declination stations in the northern hemisphere correspond to west declination stations in the southern hemisphere and vice versa.

4. By assuming horizontal stratification of density at and below some height below $h_m F2$, it is possible to get a set of results fully consistent with those of Eyfrig (1963a,b). Furthermore, it has been possible to explain why declination effects are weaker near the equator than at mid-latitudes.

5. A model of the non-symmetric behavior of the geomagnetic anomaly has been constructed based on latitudinal gradient asymmetries and this has been used to explain discrepancies between observations of the geomagnetic anomaly in the American and African-Asian zones.

Although the model offered has been presented in the simplest of configurations, the discussion has explained how modifications would alter the results. We find that the general conclusions above hold true as long as there is latitudinal component of current symmetric about the geographic equator in morning and late evening.

We note that no account has been made of solstice type conditions. Here one is forced to reconsider the results on the basis of asymmetric conditions about the equator on temperature and density gradients with respect to asymmetric solar control and adjust the results accordingly. Furthermore, our results depend on a single ionic constituent being in transport equilibrium in the region of our study. We recognize that higher altitude results may be altered by the presence of smaller mass constituents. The details of such studies will be reserved for future consideration. Studies of the predicted effects listed in this work are currently in progress using Alouette I data, and we hope to have a report available in the near future to check the degree of validity of the concepts presented herein.

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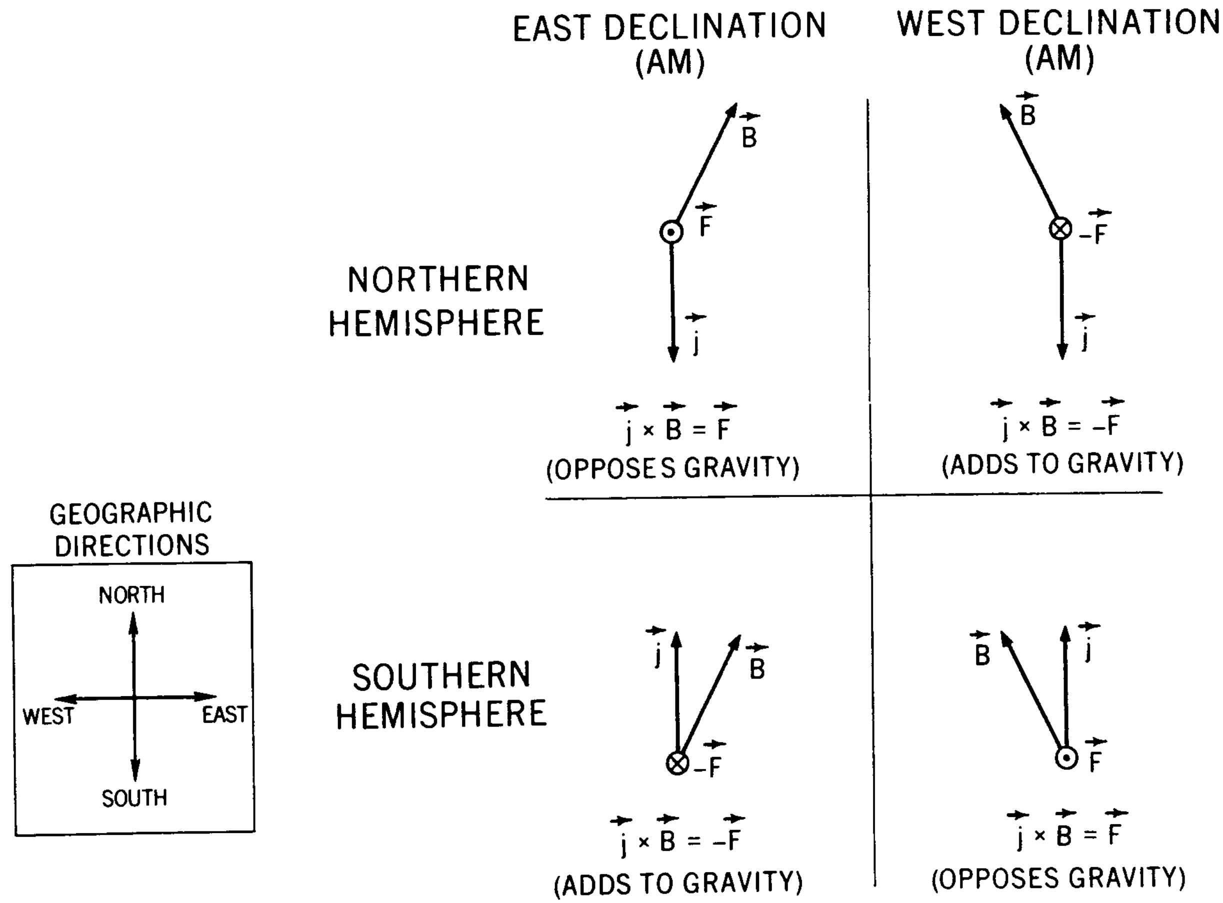

Figure 1–Vector representation of $\vec{j} \times \vec{B}$ to demonstrate the morning effect of a geographical latitudinal current component on vertical density distributions. East and west declination stations in both the northern and southern hemispheres are compared.

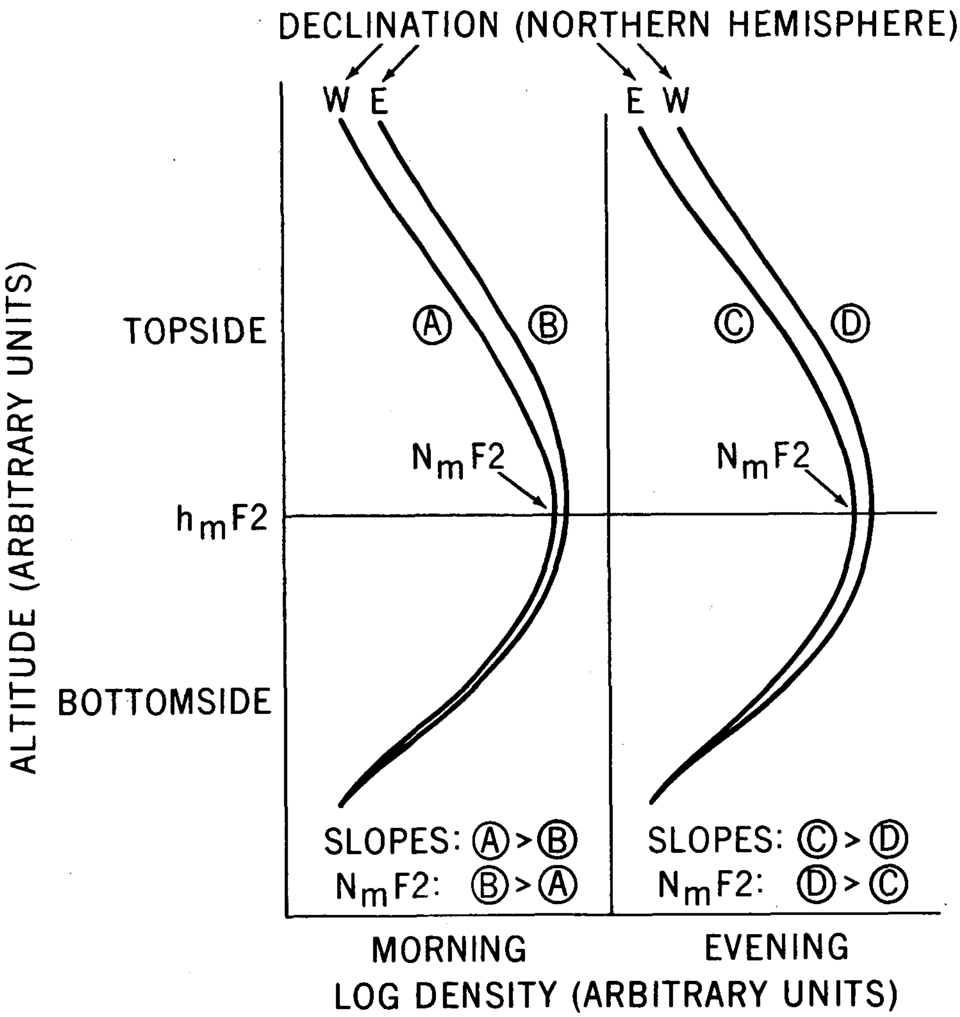

Figure 2–Possible variations in the vertical F region density distributions because of differences in $\vec{j} \times \vec{B}$. Comparison is made between northern hemisphere stations of east and west declination during both morning and evening conditions. (Opposite results occur in the southern hemisphere. Refer to Table I.) The inequalities shown for slopes refer to topside magnitude only.

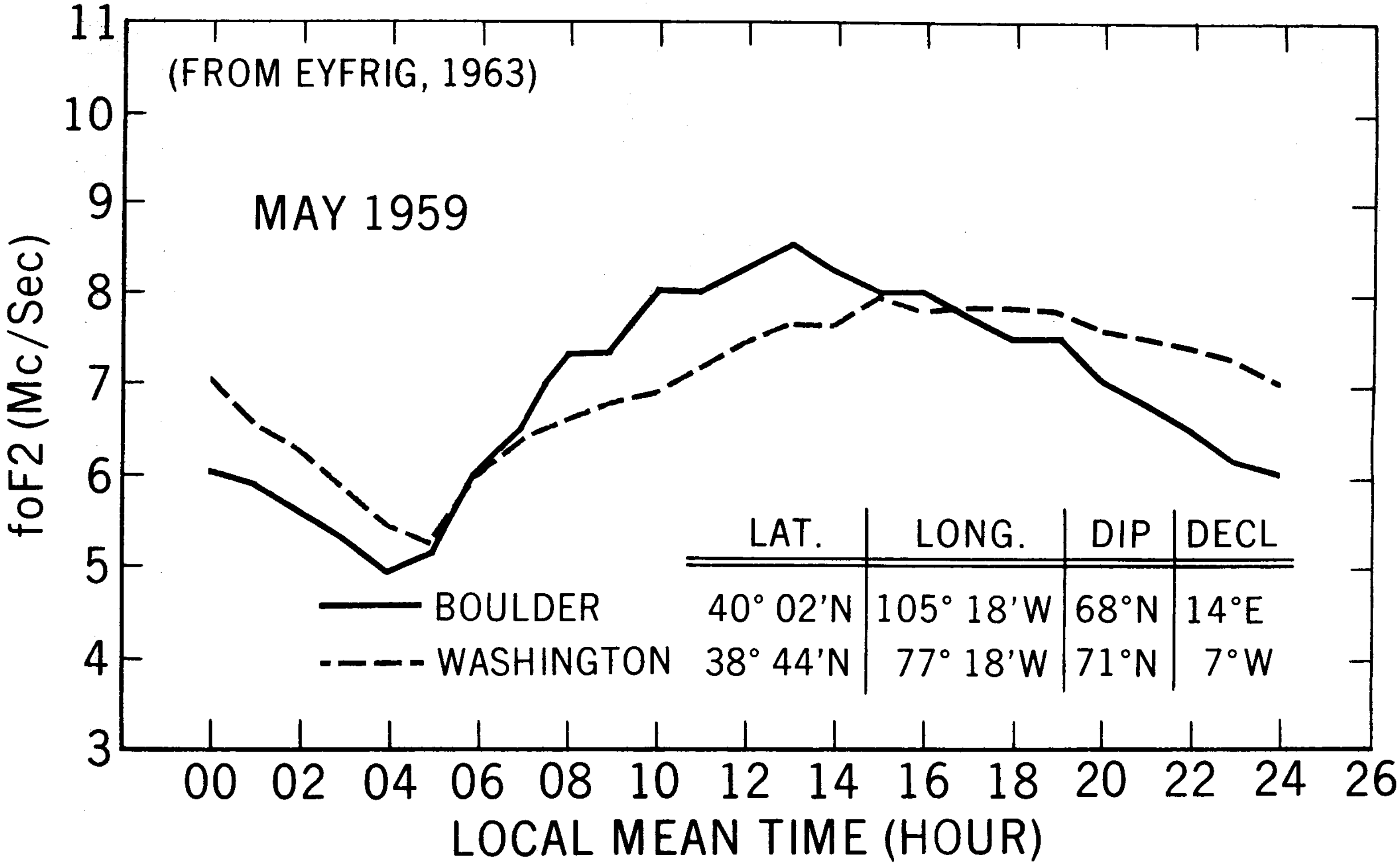

Figure 3–An example of the diurnal behavior of foF2 for two midlatitude stations possessing opposite declination. (Taken from Eyfrig, 1963b).

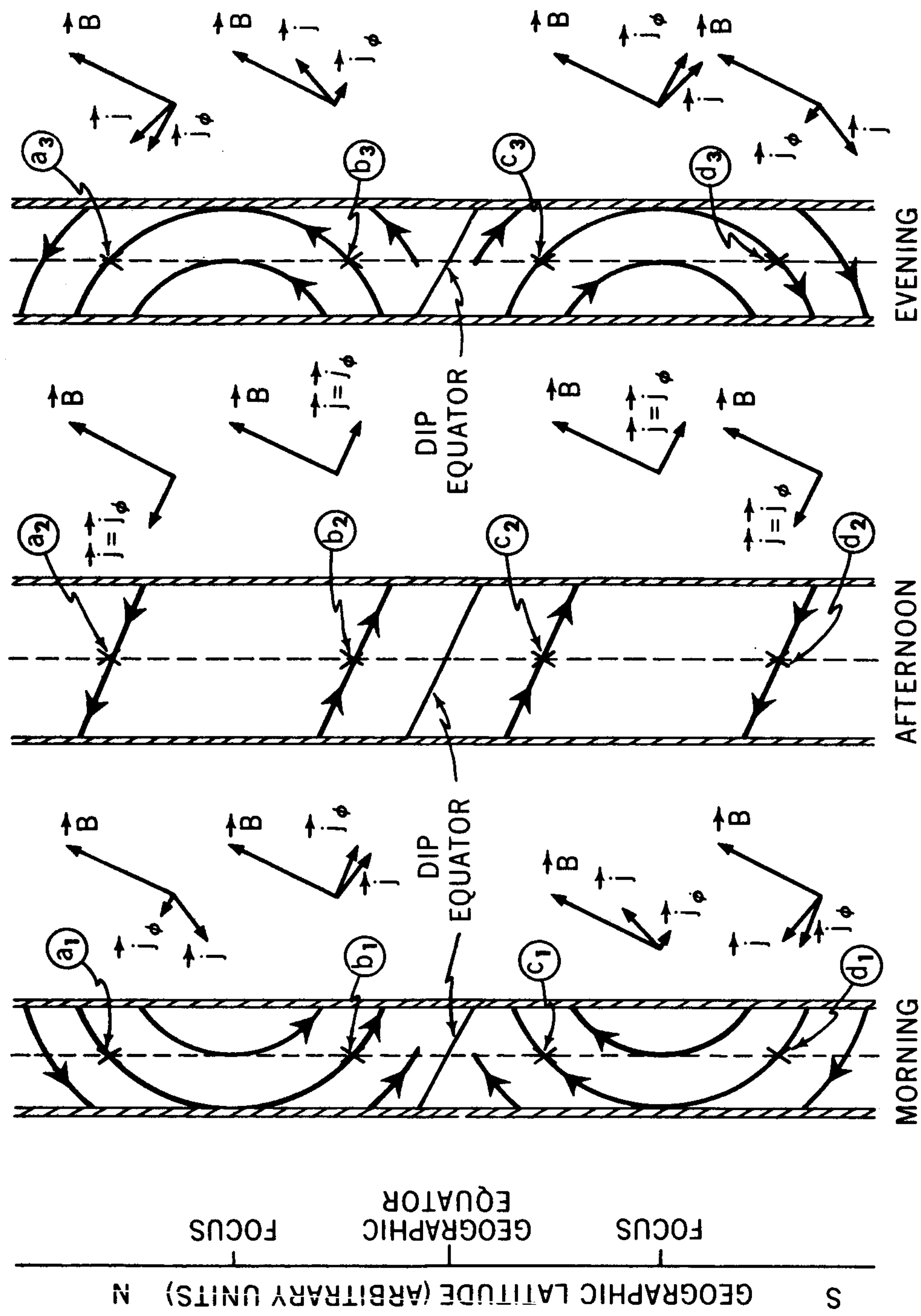

Figure 4–Vector diagrams illustrating the magnitude and direction of j_ϕ at different latitudes along a geographic meridian located in an east declination region. Morning, afternoon, and evening representations are illustrated. Regions a and d refer to the polar side of the foci; b and c, to the equatorial side. Subscripts 1, 2, and 3 refer to morning, afternoon, and evening respectively.

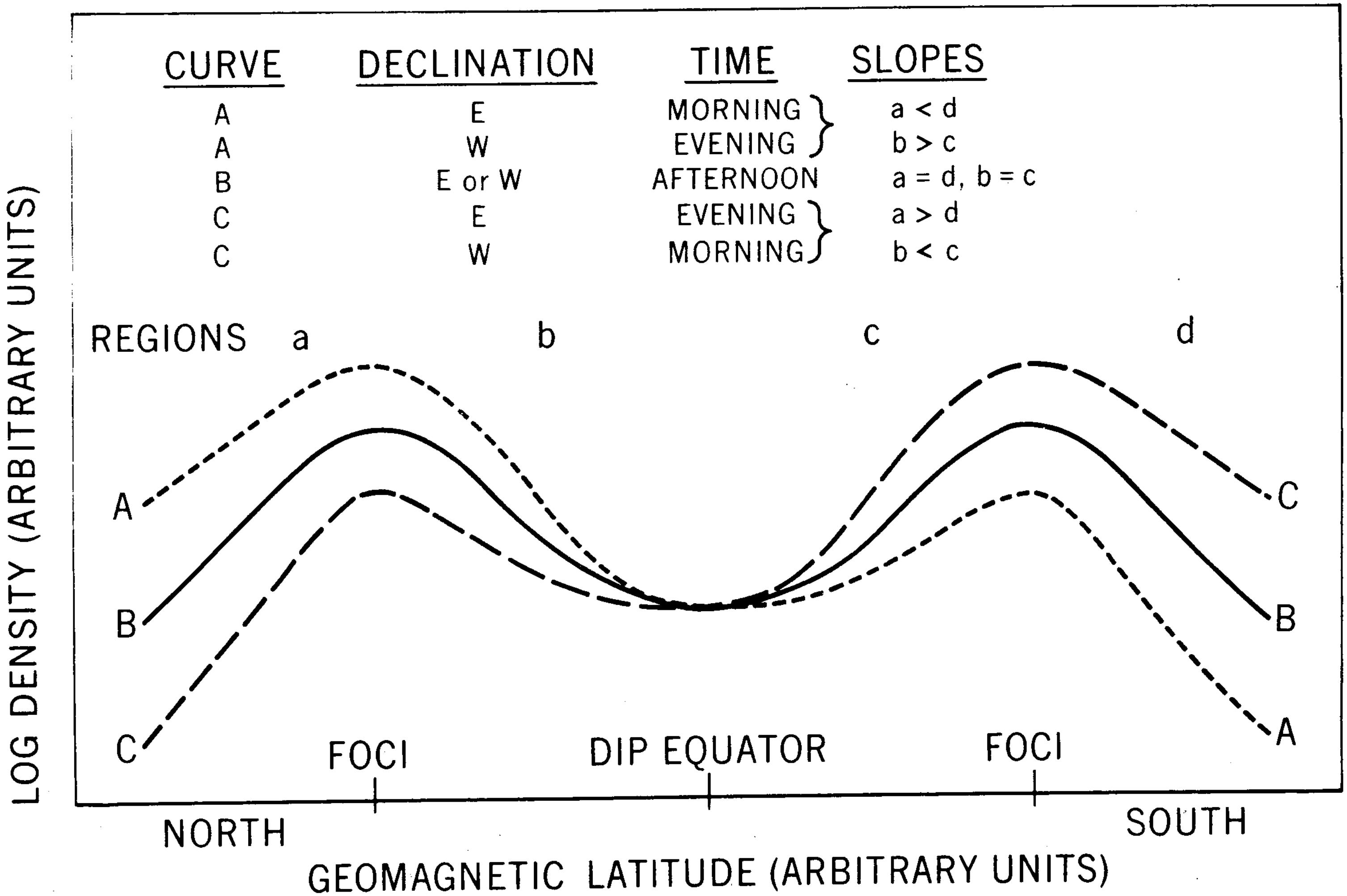

Figure 5–Possible configurations of a latitudinal constant height density profile based upon the slopes tabulated in Table III. The conditions are also briefly summarized above the curves. It is understood that slopes of regions a, b, c, and d refer to magnitude only.

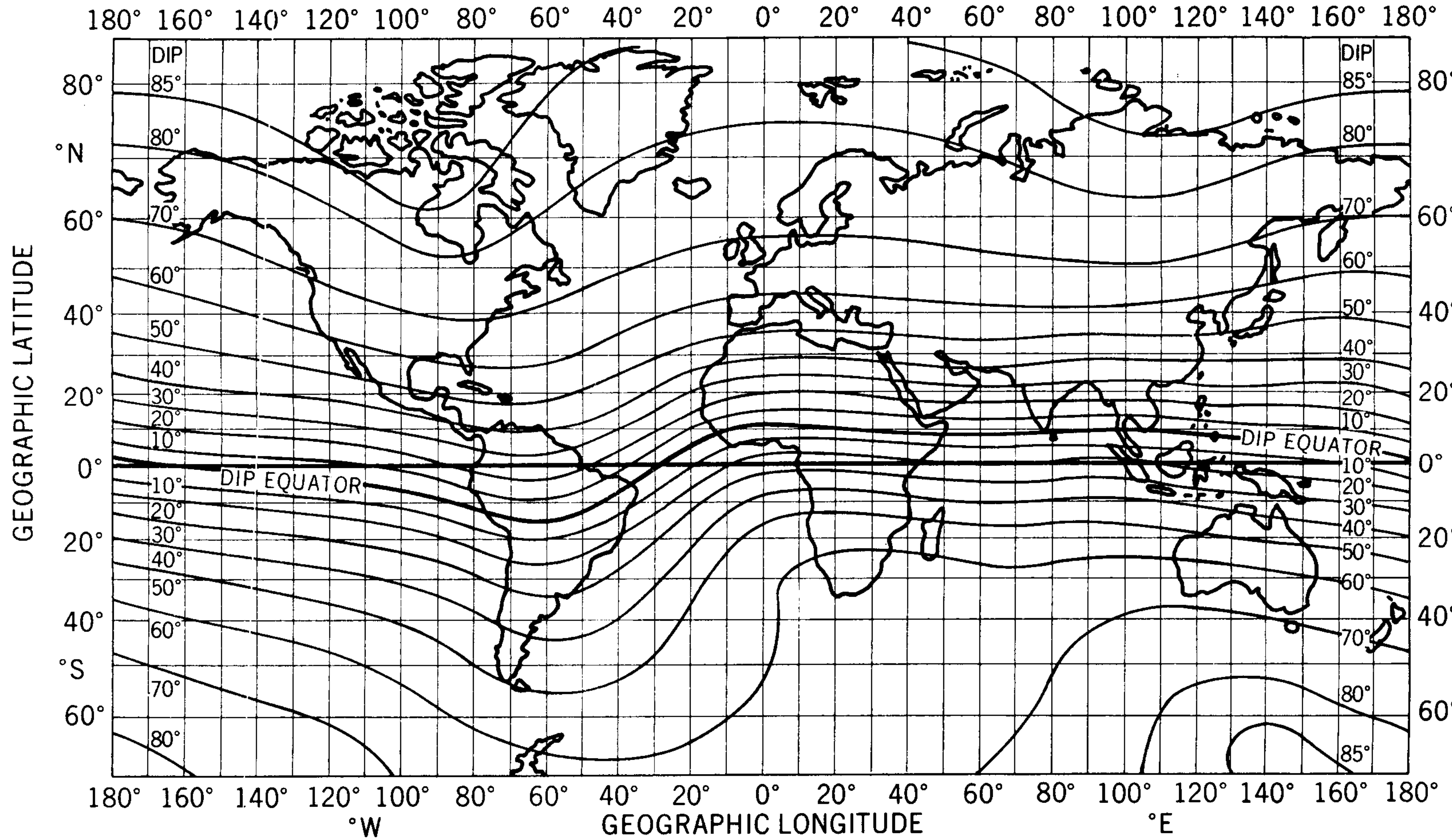

Figure 6–Worldwide representation of the Earth's magnetic field isoclines.